

CONSEQUENCES OF THE NON GAUSSIAN CHARACTER OF THE STOCHASTIC EXCITATION FOR SOLAR-TYPE OSCILLATIONS.

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Abstract

Our recent study, based on a 3D numerical simulation, suggested that the stochastic excitation of solar p -modes has a non gaussian nature and a non gaussian model was proposed which results in a good agreement between the computed rate P at which p -modes are excited and the solar seismic observational constraints.

In the present work, we study some consequences of this non-gaussian model on the rate P at which p -modes are excited in intermediate mass stars ($1M_{\odot} \lesssim M \lesssim 2M_{\odot}$). The non gaussian model changes substantially the spectrum of P at high frequency compared with the commonly assumed gaussian model. The largest effects on $P(\nu)$ are found for stars in the mass range $\sim 1.5 - 1.6 M_{\odot}$. They are found large enough that observatins in solar-like oscillating stars observed with space based seismology missions (e.g. COROT) will be able to confirm or reject the gaussian nature of stochastic excitation.

1 Introduction

Excitation of solar-type oscillations results from turbulent movements in the upper convective zone of intermediate mass stars ($1M_{\odot} \lesssim M < 2M_{\odot}$). The rate $P(\nu)$ at which a given mode with frequency ν is excited crucially depends on the time averaged and *dynamic* properties of the turbulent medium (Samadi 2001).

Different models for stochastic excitation have been proposed by several authors (e.g. Goldreich & Keeley 1977; Balmforth 1992; Goldreich et al. 1994; Samadi & Goupil 2001). The model of Samadi & Goupil (2001, Paper I hereafter, see also Samadi (2001)) takes into account the frequency dependence $\chi_k(\nu)$ of the correlation product of the turbulent velocity field. This last quantity characterizes the dynamic properties of the turbulence. This excitation model offers then the advantage to test different hypothesis concerning the dynamic properties of the turbulent medium.

A gaussian function is usually assumed for $\chi_k(\nu)$ (e.g. Goldreich & Keeley 1977). However recently, using 3D numerical simulation of the upper part of the solar convective zone, Samadi et al. (2002) have shown that the gaussian model indeed does not correctly model $\chi_k(\nu)$ in the frequency range where the acoustic energy injected into the solar p -modes is important ($\nu \simeq 2 - 4$ mHz). One must consider an additional non-gaussian component for $\chi_k(\nu)$ to reproduce its behavior. Computed values of P obtained with this non-gaussian component reproduce better the solar seismic observations.

In the present work we study the consequences of this non-gaussian component for the stochastic excitation of p -modes in intermediate mass stars. Sect. 1 describes the stochastic excitation model we consider and summarizes Samadi et al. (2002)'s results which establish the non gaussian character of the stochastic excitation. In Sect. 2 we compute P for different stellar models with

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masses in the mass range $1M_{\odot} \lesssim M \lesssim 2M_{\odot}$. In the computation we assume two hypotheses for $\chi_k(\nu)$: the gaussian function and a non gaussian function as inferred in Samadi et al. (2002) from a 3D simulation.

2 The non gaussian character of the stochastic excitation

The theoretical expression in Paper I for the excitation rate P can be written in a schematic form as :

$$P(\nu) \propto \int d\mathbf{m} \int d\mathbf{r} d\tau \vec{\xi}_r \cdot \langle \vec{S} \vec{S} \rangle(\mathbf{r}, \tau) \cdot \vec{\xi}_r \quad (2.1)$$

where \mathbf{r} and τ are related to the local turbulence : \mathbf{r} is the distance between two given points in the turbulent medium and τ is the time correlation between the two distant points (τ is associated with the eddy lifetime which is typically much shorter than the oscillations lifetime). In Eq. (2.1), ξ_r denotes the radial mode eigenfunction and $\langle \vec{S} \vec{S} \rangle$ the correlation product of the excitation source versus \mathbf{r} and τ . The excitation source (\vec{S}) originates from the turbulent Reynolds stress and the advection of the turbulent entropy fluctuations by the turbulent motions. $\langle \vec{S} \vec{S} \rangle$ is expressed in terms of the turbulent kinetic energy spectrum $E(k, \nu)$ and the spectrum of the entropy fluctuations $E_s(k, \nu)$ where k is the wavenumber of a given turbulent element. Further $E(k, \nu)$ is split into a spatial component $E(k)$ and a frequency component $\chi_k(\nu)$ according to Stein (1967) as $E(k, \nu) = E(k) \chi_k(\nu)$. The same decomposition is assumed for $E_s(k, \nu)$.

In the calculation of $P(\nu)$, a gaussian shape is usually assumed for $\chi_k(\nu)$ (e.g. Goldreich & Keeley 1977). This assumption is equivalent to suppose that two distant points in the turbulent medium are uncorrelated. Such Gaussian function (GF hereafter) has the form

$$\chi_k^{\text{GF}}(\nu) = \frac{1}{\nu_k \sqrt{\pi}} e^{-(\nu/\nu_k)^2}, \quad (2.2)$$

where ν_k is the line-width at half maximum.

With the help of a 3D numerical simulation of the upper part of the solar convective zone, it is found in Samadi et al. (2002) that the GF does not reproduced correctly the frequency dependence of χ_k inferred from the 3D simulation. In contrat, χ_k is better modeled by the Gaussian plus an Exponential function (GEF hereafter) as:

$$\chi_k^{\text{GEF}}(\nu) = \frac{1}{2} \left(\frac{1}{\nu_k \sqrt{\pi}} e^{-(\nu/\nu_k)^2} + \frac{1}{2\nu_k} e^{-|\nu/\nu_k|} \right). \quad (2.3)$$

3 Consequences for solar-like oscillating stars

We compute several stellar models with masses $M = 1., 1.2, 1.5, 1.65, 1.85, 2. M_{\odot}$ and with the same age (650 My). Calculations are carried out with the CESAM evolutionary code in which the convective heat flux is computed according to the classical mixing-length theory by Böhm-Vitense (1958). The eigenfunctions are obtained from the adiabatic FILOU pulsation code by Tran Minh & Leon (1995). The input physics are similar to those of Samadi et al. (2001) except for the atmosphere which is computed with the Eddington classical gray atmosphere for sake of simplicity.

We compute P for each the stellar model according to Eq. (2.1). In the calculation, we assume successively for $\chi_k(\nu)$: the gaussian model (GF, Eq. 2.2) and the non gaussian model (GEF, Eq. 2.3). A scaling factor is introduced such that for the solar model the maximum in P matches the solar seismic constraints by Chaplin et al. (1998). Results are presented in Fig. 1.

For all stellar models, the largest differences in P between calculations performed with the GF and those performed with the GEF are obtained for $\nu \gtrsim \nu_{\text{max}}$ where ν_{max} is the frequency at which P is maximum. This feature is a direct a consequence of the difference in the frequency dependence of the GF and the GEF. Indeed, the GEF decreases with ν slower than the GF does for $\nu \gtrsim \nu_k$. Moreover ν_{max} scales approximatively as $\bar{\nu}_k$ where $\bar{\nu}_k$ is the characteristic frequency associated with the largest energy-bearing eddy located at the top of superadiabatic (this is the region where the excitation is the largest). The eddies who excite the most the modes have their characteristic frequency $\nu_k \simeq \bar{\nu}_k$. Consequently for $\nu \gtrsim \nu_{\text{max}}$ a larger amount of acoustic energy is injected with the GEF than the GF.

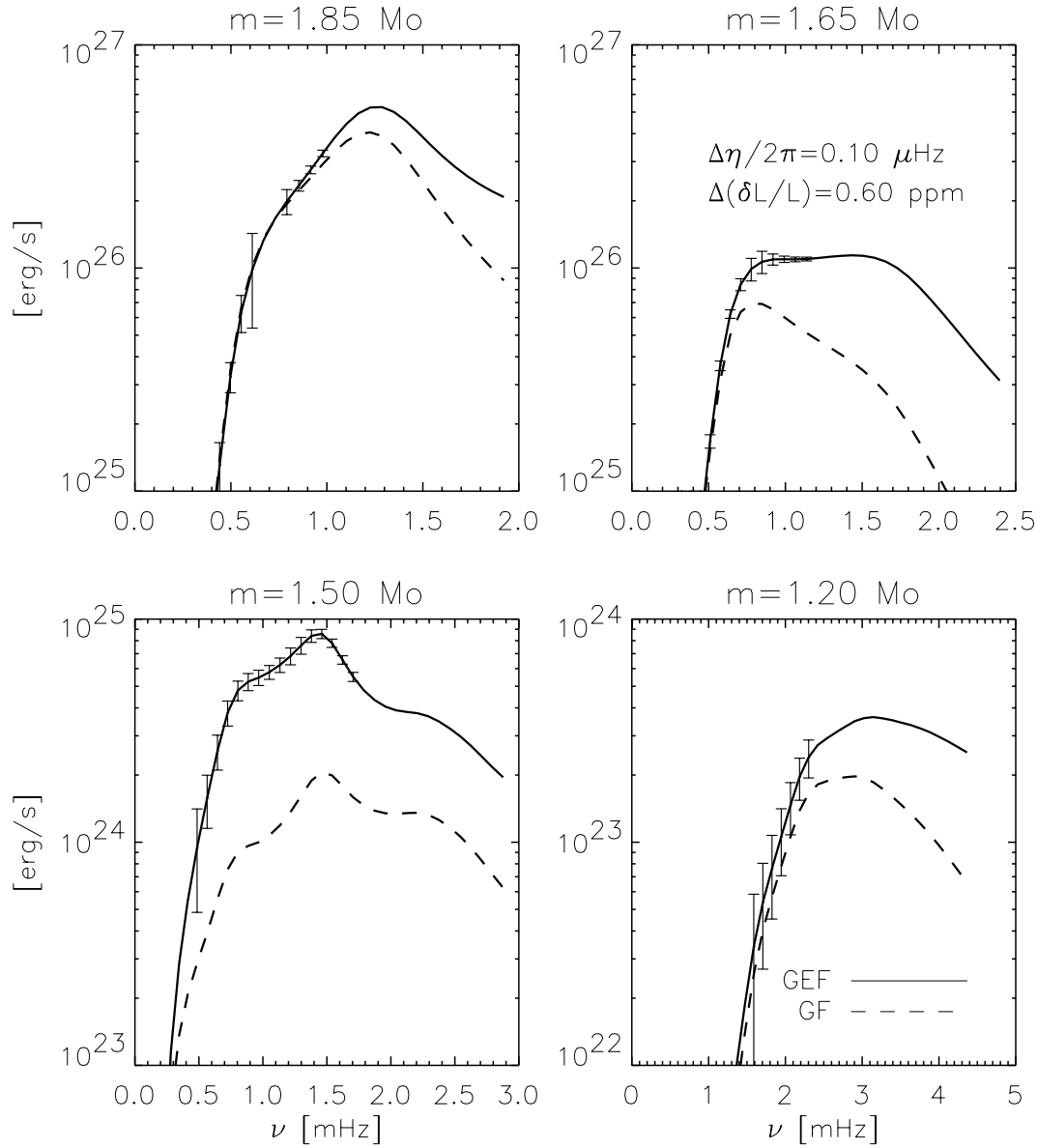


Fig. 1. The excitation rate P at which stellar p -modes are excited is computed for several stellar models with masses $M = 1.2, 1.5, 1.65, 1.85 M_{\odot}$. Two different analytical functions are assumed for $\chi_k(\nu)$: the GF (dashed curve, Eq. 2.2) and the GEF (solid curve, Eq. 2.3). Vertical error bars ΔP are estimated in the manner of Samadi et al. (2001). The assumed accuracy in the measurement of the mode damping rates (η) and the mode relative luminosity fluctuations ($\delta L/L$) are based on the expected performances of the COROT mission (Baglin et al. 1998) (i.e. $\Delta\eta/2\pi = 0.1 \mu\text{Hz}$ and $\Delta\delta L/L = 0.6 \text{ ppm}$). Values of η are calculated in the manner of Houdek et al. (1999).

The largest effects in P of the dynamic model adopted for χ_k are obtained for the $M = 1.5 M_{\odot}$ and $M = 1.65 M_{\odot}$ stellar models: Let ΔP be the difference in P between calculations performed with the GF and those performed with the GEF. ΔP is found larger for these two models than for the other stellar models. Moreover ΔP takes large values over a larger range in ν/ν_c where ν_c is the cut-off frequency (ν_c delimits the extend of frequency domain where modes have a significant amplitude). These features are due to the fact that the characteristic turbulent Mach number, M_t , is the highest for stars with mass $\sim 1.5 - 1.6 M_{\odot}$. Indeed, ΔP_{max} , the maximum in ΔP , scales approximatively as $\bar{\nu}_k^3 \Delta\chi_k$ where $\Delta\chi_k \equiv \|\chi_k^{\text{GEF}} - \chi_k^{\text{GF}}\|_{\nu=\bar{\nu}_k}$. As $\Delta\chi_k$ scales as $\bar{\nu}_k^{-1}$ and $\bar{\nu}_k$

scales approximatively as $M_t \nu_c$, ΔP_{\max} increases then as M_t^2 . Moreover, let $\Delta\nu$ be the frequency domain where $\|\Delta P - \Delta P_{\max}\| < \epsilon \Delta P_{\max}$ where ϵ is arbitrarily fixed to a value $\ll 1$. In other words $\Delta\nu$ defines a domain where ΔP is “large”. One shows that $d^2 \Delta \chi_k / d\nu^2$ scales as $\bar{\nu}_k^{-3}$ and then $d^2 \Delta P / d\nu^2 \propto \bar{\nu}_k^{-2} \Delta P_{\max}$. As a consequence $\|\Delta P - \Delta P_{\max}\| \approx \frac{1}{2} \bar{\nu}_k^{-2} \Delta \nu^2 \Delta P_{\max}$. The domain $\Delta\nu / \nu_c$ then scales as $\sqrt{\epsilon} \bar{\nu}_k / \nu_c \propto M_t$.

4 Conclusion

The present work illustrates that a non gaussian model of stochastic excitation substantially changes the shape and the magnitude of the calculated excitation spectrum P of the oscillations in intermediate mass star more massive than the Sun. Differences in P between computation carried out with the non gaussian excitation model and this carried out with the common gaussian model are found larger for the frequency modes above the frequency ν_{\max} at which P peaks. The largest effects are expected for stars in the mass range $\sim 1.5 - 1.6 M_{\odot}$. They are found large enough to be discriminate from space based experiences with performances equivalent or higher than those of the COROT intrument (Baglin et al. 1998).

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